Weather-Rated Economics of Gas Turbine Installations

A Call for an Alternate Rating Point

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Introduction

The economic status of most of the US's gas turbine installations remains bleak, as of late 2005. The gas-fired generation capacity that once showed so much promise now struggles to maintain a foothold in real contributions to the national grids. The gas turbine is far from dead, yet the immediate future of this technology looks to be much less robust as compared to the boom days of 1998-2001.

The US power industry now lives with remarkably low capacity factors for gas-fired gas turbine plants. Gas-fired Combined Cycle (CC) plants were supposed to take on the bulk of the base load in the US, allowing older coal-fired plants to retire gracefully. Instead, the market has called for a renewed emphasis on coal-fired operations. Many of the older coal plants are receiving a new economic lease on life through renewed capital improvements that were needed to clean up emissions. Future greenfield coal plants promise to be extremely clean as compared to previous generations. In fact, the cleanest coal-fired technology in the next decade should be the Integrated Gasification Combined Cycle (IGCC) that marries the low cost of coal with the high efficiency of gas turbine combined cycles. Therefore, the future of coal looks to be headed "back to the future" with gas turbines.

The question is, "where does that leave current and future *gas-fired* gas turbines?" The obvious answer is that these plants will continue to serve, and will even grow in numbers, but at rather low capacity factors. Because both base load and peaking period electrical demand continues to rise unabated, gas-fired gas turbines will still have their place in the generation mix. However, CC plants that were designed to be base-load operations are running at intermediate load at best, and even are forced into daily peaking operations.

Unable to find an attractive market for their power, many CC plants from the boom era have defaulted on their debt obligations, wiping out not only equity positions of their developers and investors, but also much of the capital covered by debt. A CC plant, which may have originally been valued at $600 per kW when natural gas was originally priced at $2 per mmBTU, might have had a residual value of $300 per kW when gas then rose to $5. One has to wonder if we will soon face another round of CC plant "fire sales" due to the plant devaluation associated with gas prices exceeding $10.

Just how bad is the capacity factor issue? One of the best representations of this phenomenon has recently been provided by Jeffrey Phillips of the Electric Power Research Institute (EPRI). In an article[1] published earlier in 2005, he graphically (next page) demonstrates the declining annual capacity factors for CC plants in the US.

While the downward trend in average annual capacity factor (the red line) is frightening enough, what is even more noteworthy is the increasing spread (black line) between

[1] Turbomachinery International, July 2005, Jeffrey Phillips "Putting Combined Cycles Back in Use"

winter capacity factor as compared to summer. In simplistic terms, the summer capacity factor for 2004 was double that of the winter capacity factor. The trend is clearly for this seasonal spread to grow, as gas prices remain high relative to coal. It will be interesting to see what this information looks like for 2005, when natural gas prices just about doubled over the course of the year.

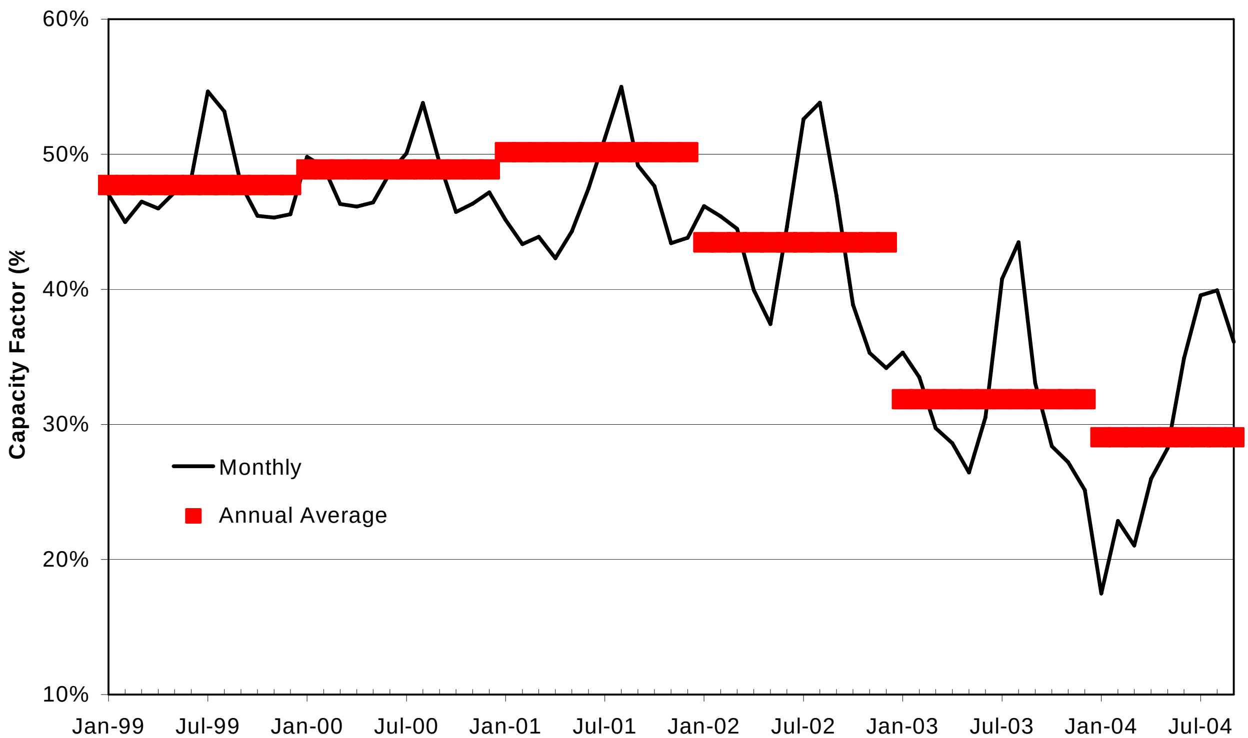

Figure 1 – Monthly and Annual Capacity Factors of US Combined Cycle Fleet. Source: EPRI Report 1008329, March 2005, *Gas Market Transition: Impacts of Power Generation on Gas Pricing Dynamics.*

For 2004, the capacity factor low point was 18% for January, and the high point 40% for August. However, the above figure shows monthly averages. If this figure could show daily and average hourly capacity factors, it is easy to surmise that the weekday capacity factors would be much higher than the weekend/holidays. Further, the capacity factors for the daily peak hours would be much higher than the overnight hours. To put this in perspective, a typical CC operating realm in the summer is a 5 X 16 dispatch block. This is 80 hours per week, or 47% capacity factor. Therefore, the graphical spread between winter and summer operating seasons in the figure above actually understates the overall spread in capacity factor, experiencing a nadir in off-peak shoulder-season hours, as compared to the super-peak of summer daytime operations.

When these CC plants were in the planning and design phase some five to seven years ago, the economic assumption for capacity factor was for greater than 80% for most plants, and as much as 95% by the most optimistic. Accordingly, several design assumptions have come back to haunt those original assumptions. The issue that gets the most press is the fact that daily cycling of CC plants is causing problems with the Heat Recovery Steam Generator (HRSG) and steam turbine plant. Daily cycling is also causing the "engine starts" portion of many Long Term Service Agreements (LTSA) to get rather expensive.

The second design issue from that period, much less publicized, is that the plant was probably optimized for an ambient temperature based on the local annual average temperature, or at best, the summer average temperature. Many plants were optimized for temperatures that ranged from 59°F (10 C) and 77°F (25C). This issue has been the subject of past papers by TAS. In those papers, we demonstrated that optimization of a CC plant for high ambient temperatures, say 95°F (35C), when including turbine inlet cooling (TIC), resulted in better than a 53.7 MW[2] increase in power for a typical 500 MW *nameplate* plant. If that plant were in fact optimized for a lower *summer average* temperature such as 77°F, as compared to 95°F, the loss in power would be approximately 2.5 MW[3] at the peak earning periods, even with the same capital costs.

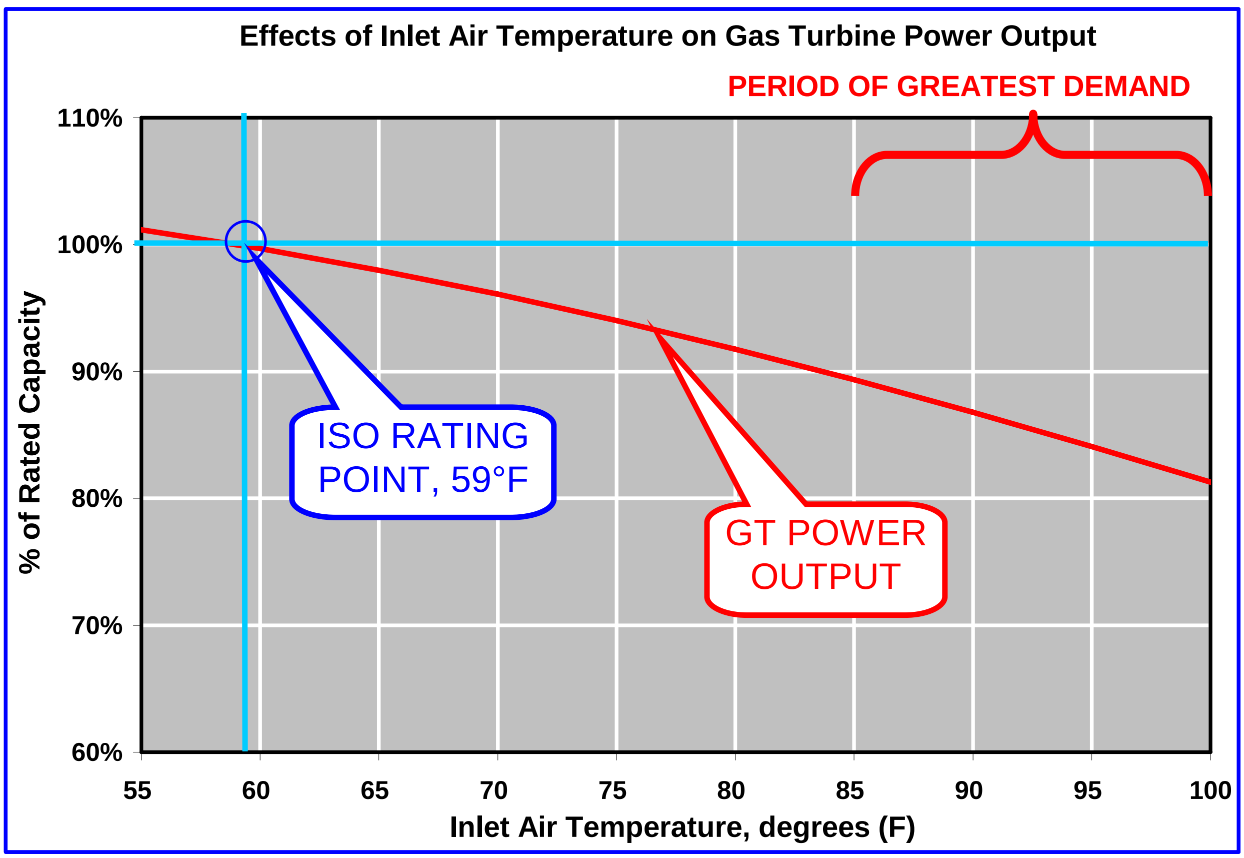

Figure 2 – Gas Turbine Power Output, as compared to the compressor Inlet Air Temperature. The slope of this line is called the "Lapse Rate". The gas turbine chosen for this figure is a very common aeroderivative peaker. All gas turbines have unique lapse rates.

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[2] Tillman, Turbine Air Systems, PowerGen International 2003, "Comparison of Power Enhancement Options for Greenfield Combined Cycle Power Plants"

[3] Tillman, Turbine Air Systems, PowerGen International 2004, "Comparison of Power Enhancement Options for Retrofit to Combined Cycle Power Plants, Phase 2 Report"

EPRI's Phillips contends that one potential use for US CC plants suffering from low capacity factor would be to repower[4] them as the starting point for a new IGCC project. This would certainly save significant capital costs as compared to a new power block, albeit that a considerable amount of modification to the existing power block would still be required to allow the units to run on syn-gas (a combination of carbon monoxide and hydrogen). This is a commendable idea, and will probably be implemented. However this concept is not likely to make a large enough impact on the total GT market to save many CC installations from further devaluations.

Dedicated peakers, mostly simple-cycle (SC) aero-derivative turbines, continue to be slowly added in areas strapped for increased peaking load. In general for gas turbines, the US SC market appears to be stronger than the CC market, but only in relative terms. Certainly, SC peakers that will be installed in the coming years will be required only to serve the summer peaking load caused mostly by air conditioning. In fact, the so-called "generation glut" of the past four years in the US is not a glut at all during hot summer afternoons. There is once again growing strain in regions such as California and New England with peak capacity reserve margins now all but eliminated in the summer season.

The point now stands – "What have we learned in the US power industry, regarding the design of these GT assets?" The answer, we believe, is that the industry failed to consider that the most profitable period of operation for CC plants, perhaps the *only* period of profitable operation, is the summer daytime peaks. This trend was as predictable then as its continuation continues to be now.

On an international basis, SC and CC installations continue to grow in the tropical and subtropical regions of the world. Growth continues unabated in China, Southeast Asia and the Middle East. In fact, in these regions of the world, their seasons are predominantly "hot" and "hotter".

Our contention is that gas turbine assets, including CC plants, not only should be optimized for hot weather operations, but also should be *rated* at high ambient temperatures. The current rating of gas turbines is the "ISO" point of 59°F (15C). Even though many combined cycle plants are sometimes tested at prevailing temperatures, the test data is usually then "corrected" back to the standard ISO design point of 59°F.

In today's markets, gas turbine assets are called into duty at warm-to-hot ambient temperatures, and also at very cold temperatures. We don't hear of cold weather *electric* supply problems, even though there is sometimes tightness in fuel supply. The point is that gas turbines are *least* likely to run in the moderate ambient temperature band, centered ironically around 59°F! Therefore, the current ISO rating point has become irrelevant, and a relic of past practices. We believe that the economic reality of gas turbine operations dictate that a new, if perhaps alternative, rating point is now warranted.

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4 Turbomachinery Int'l, July 2005, Jeffrey Phillips "Putting Combined Cycles Back in Use"

Making the Case for an Alternative Design Point

The ISO rating point of 59°F (15 C) and 40% RH is ingrained in the memory of every power engineer that works with gas turbines. We now recommend a new, alternative-rating point for gas turbines that represents the economic reality of operations for GTs. Such a convention would not be a first, because marine applications for engines (including gas turbines) have long used a much higher ambient temperature, 100°F.[5]

The new rating point that we recommend is 95°F (35 C) and 60% RH. There are several reasons for this point.

- A line drawn between the current ISO rating point and the proposed alternative rating point is a good "best fit" match for the design conditions of several major US cities. These hot weather design points are prescribed by the American Society of Refrigeration Heating and Air-conditioning Engineers (ASHRAE). This reference is considered the most authorative source of design weather data for a single "snap-shot" temperature and humidity point.

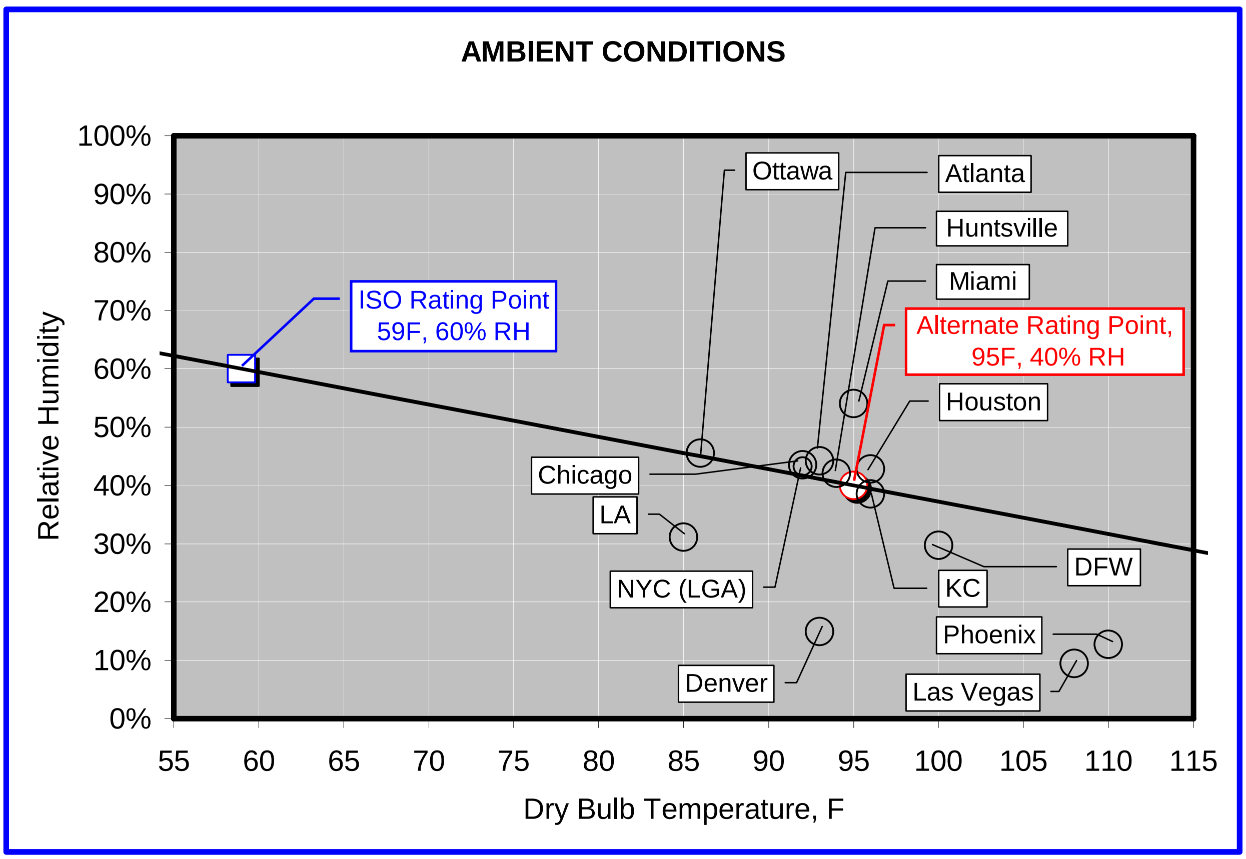

Figure 3 – ASHRAE Design Conditions for several US locations, plotted as RH vs. ambient Dry Bulb temperature in degrees F.

[5] MIL-E-17341C, 1962, 1970 "Military Specification, Engines, Gas Turbine, Propulsion and Auxiliary Naval Shipboard", specifies 100 F

- These ASHRAE design points are also published for hundreds of cities around the globe. Most specifying engineers and owners recognize this data reference. The concept of a single "best fit" line is harder to establish in the span of global locations. Nonetheless, the 35 C design point is a reasonable proxy for summer design conditions internationally, as it is in the US. For the Persian Gulf Region (as in the US Desert Southwest), the design point understates the design dry bulb temperature and overestimates the humidity conditions. However, as in the previous figure, the argument is to move as far as reasonably necessary from the current ISO rating point as possible, not to cover every possible extreme.

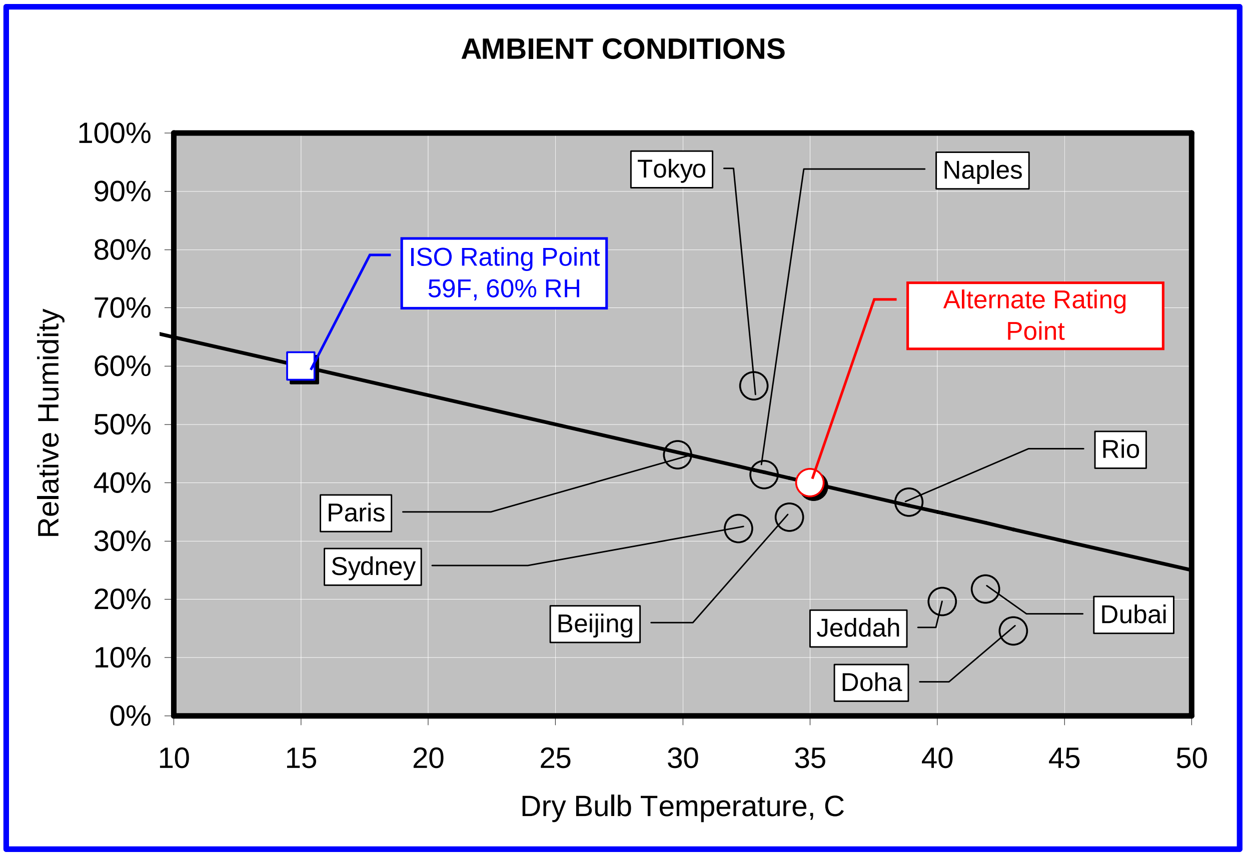

Figure 4 – ASHRAE Design Conditions for several international locations, plotted as RH vs. ambient Dry Bulb temperature in degrees C.

- Like 59°F and its SI counterpart of 15 C, the 95°F / 35 C temperature pairing is at a whole number for each scale. This makes the point as attractive to those countries that still use the Fahrenheit scale, as well as the remainder of the world who uses Celsius (Centigrade) scale.

- Heat rejection equipment for dry chilled water applications is often rated at 95°F (35 C), as by example ARI 590-1999.

- Heat rejection for water-cooled chiller applications is determined by a “wet bulb” (WB) temperature of 75°F, per ARI 550-1990, which is tantalizingly close to the WB temperature that corresponds to 95°F / 60% RH (actually 75.06 F).

City	State	Country	Dry Bulb 0.4%	MCWB
Los Angeles	CA	USA	85	64
Las Vegas	NV	USA	108	66
Chicago	IL	USA	91	74
Houston	TX	USA	96	77
New York City	NY	USA	91	74
Miami	FL	USA	91	77
Atlanta	GA	USA	93	75
Paris		France	86	69
Tokyo		Japan	91	78
Beijing		China	94	71
Shanghai		China	94	81
Jeddah		Saudi	104	72
Doha		Qatar	109	71
Rio de Janeiro		Brazil	102	79
Dubai		UAE	107	75
Kuala Lumpur		Mayalasia	94	78
Seoul		So Korea	89	77
Average			95.6	74.0
Standard Deviation			7.59	4.65

Table 1, ASHRAE DB and MCWB design points for several major cities

It is easy to put together a list of major international cities and the ASHRAE design conditions for Dry Bulb temperature and its Mean Coincident Wet Bulb (MCWB) temperature. As one can see, the temperatures tend to fall to the 95 DB / 75 MCWB pairing (this also can be described as 95F and 40% RH).

It is particularly critical that the proper *coincident* RH value is quoted for the design dry bulb temperature. This is the overwhelming first error that we see in design-basis specifications for gas turbine projects. The error is usually manifested in describing the maximum site RH in a way that it is *coincident* with the maximum annual dry bulb temperature. Such extremes never occur simultaneously. In fact, power engineers would do well to avoid “RH” altogether and to use the more appropriate term of *coincident* WB. This admonition might seem strangely unnecessary to veteran engineers who have worked with cooling towers for decades. However, the newer generation of engineers, who might be wizards at CAD and FEA, seem blissfully unaware of even rudimentary psychrometric principles.

Weather-Leverage Capital Cost of Gas Turbine Plants

When an Owner or an engineer asks a question regarding a particular gas turbine, the usual first question would be "what is its output"? To date, the proper answer would be that "its output at the *ISO Rating Point of 59°F* (35C) would be ___ MW." In this section, we ask the output question with more precision" "what is the *useful* output of this gas turbine during the most likely temperature of profitable operation?"

One can look to references such as *Gas Turbine World*'s annual Handbook[6] where all of the available gas turbines are listed with such standard data, all at the ISO rating point. One of the most interesting features of such a list is to look at the *unit cost* of gas turbines, and their built-out CC plants. The unit cost is expressed as "$ per kW". As such, this parametric figure is a *value* determination. Of course, this figure needs to be considered in light of heat rate parametric of "BTU per kWHr"; yet even this efficiency proxy is dependent on rating at the common ISO point.

GT OEM	Model	Version	ISO Output, gross	Output at 95F, gross	delta power	delta temp	Lapse Rate	Specific Lapse Rate
			kW	kW	kW	°F	kW per °	% per °F
Alstom	**GT11**	N2	115,350	99,611	(15,739)	36	(437)	-0.38%
Alstom	**GT11**	NM	89,600	75,638	(13,962)	36	(388)	-0.43%
Alstom	**GT13**	E2	172,300	147,661	(24,639)	36	(684)	-0.40%
GE	**PG5371**	PA	26,555	22,009	(4,546)	36	(126)	-0.48%
GE	**PG6581**		42,600	36,706	(5,894)	36	(164)	-0.38%
GE	**PG7241FA**	SC	171,100	147,000	(24,100)	36	(669)	-0.39%
GE	**PG7241FA**	CC	498,000	454,800	(43,200)	36	(1,200)	-0.24%
GE	**LM2500**	PE	22,775	19,689	(3,086)	36	(86)	-0.38%
GE	**LM6000**	Sprint, DLN	46,857	38,330	(8,527)	36	(237)	-0.51%
GE	**LM6000**	PC w/o IGV	43,915	29,457	(14,458)	36	(402)	-0.91%
GE	**LM6000**	PD, DLN	42,533	30,849	(11,684)	36	(325)	-0.76%
MHI	**MF111B**		14,838	12,517	(2,321)	36	(64)	-0.43%
PWPS	**FT-8**	Twin	51,350	41,556	(9,794)	36	(272)	-0.53%
PWPS	**FT-8+**	Twin	56,220	46,482	(9,738)	36	(271)	-0.48%
RR	**Trent 50**		52,157	40,039	(12,118)	36	(337)	-0.65%
Solar	**Titan 130**		14,245	11,657	(2,588)	36	(72)	-0.50%
Solar	**Taurus 60**	T7800	5,500	4,641	(859)	36	(24)	-0.43%
SWPC	**GT 10**	B	24,630	20,319	(4,311)	36	(120)	-0.49%
SWPC	**GT 10**	C	29,060	24,027	(5,033)	36	(140)	-0.48%
SWPC	**GT 35**		17,015	11,724	(5,291)	36	(147)	-0.86%
SWPC	**GTX100**		43,000	36,646	(6,354)	36	(177)	-0.41%
SWPC	**W251**	B11-12	49,500	41,527	(7,973)	36	(221)	-0.45%

Table 2 Lapse Rate between 59F and 95F for selected gas turbines

If such lists of gas turbines were to be published at the proposed alternative rating point of 95°F (35C), the list would look strikingly different. First, all of the gas turbine outputs would be some 10 to 30% lower; and the heat rates would be approximately 5% higher. The drop of GT output vs. a change in temperature can be easily quantified, and is called the "lapse rate". Lapse rate can be expressed as change in kW per degree, or

[6] Pequot Publishing

percentage change per degree. The previous table shows several common gas turbines, representing both relatively older technology and newest technology.

Yet to determine the actual value of the particular gas turbine at the alternative rating point, the following table is provided. This table lists the same gas turbines; but lists the installed cost of the unit. The power output is given at both the ISO and the alternate rating points. Using the installed cost, we can determine the relative value of each turbine at the more economically relevant alternate design point. It is here that we see the real unit cost of a gas turbine is much higher than expected when considered during the real high-temperature operating periods.

For data consistency Costs and output for these tables are taken from multiple runs of Thermoflow Software's GTPro and PEACE programs.

GT OEM	Model	Version	Bare Cost	Installed Cost	ISO Output, gross	Unit Cost @ ISO,	Output at 95F, net	Net Unit Cost @ 95F
			USD	USD	kW	$ / kW	kW	$ / kW
Alstom	**GT11**	N2	$21,430,000	$39,423,560	115,350	$342	98,400	$401
Alstom	**GT11**	NM	$16,778,000	$31,897,059	89,600	$356	74,570	$428
Alstom	**GT13**	E2	$29,477,000	$52,883,930	172,300	$307	146,000	$362
GE	**PG5371**	PA	$8,400,000	$16,429,308	26,555	$619	21,610	$760
GE	**PG6581**		$11,832,000	$22,007,985	42,600	$517	36,130	$609
GE	**PG7241FA**	SC	$31,250,000	$50,701,500	171,100	$296	146,500	$346
GE	**PG7241FA**	CC	$0	$212,400,000	498,000	$427	442,700	$480
GE	**LM2500**	PE	$9,569,000	$16,958,763	22,775	$745	19,370	$876
GE	**LM6000**	Sprint, DLN	$13,670,000	$24,032,157	46,857	$513	37,800	$636
GE	**LM6000**	PC w/o IGV	$10,910,000	$20,264,567	43,915	$461	29,000	$699
GE	**LM6000**	PD, DLN	$11,507,000	$20,951,135	42,533	$493	30,390	$689
MHI	**MF111B**		$6,512,000	$12,121,797	14,838	$817	12,260	$989
PWPS	**FT-8**	Twin	$15,746,000	$28,145,580	51,350	$548	40,950	$687
PWPS	**FT-8+**	Twin	$17,189,000	$30,250,300	56,220	$538	45,830	$660
RR	**Trent 50**		$17,094,000	$29,124,686	52,157	$558	39,470	$738
Solar	**Titan 130**		$5,081,000	$9,979,823	14,245	$701	11,410	$875
Solar	**Taurus 60**	T7800	$2,174,000	$4,935,830	5,500	$897	4,522	$1,092
SWPC	**GT 10**	B	$7,871,000	$15,365,096	24,630	$624	19,950	$770
SWPC	**GT 10**	C	$8,910,000	$16,404,096	29,060	$564	23,591	$695
SWPC	**GT 35**		$6,292,000	$12,132,993	17,015	$713	13,110	$925
SWPC	**GTX100**		$12,351,000	$22,574,088	43,000	$525	36,090	$625
SWPC	**W251**	B11-12	$13,357,000	$24,648,037	49,500	$498	40,840	$604

Table 3 UNIT COST at rating points of 59F and 95F for selected gas turbines

In Table 3, we see that the unit cost of the GT is much higher when rated at the alternate design point. The reason for using this data is because what we really want to know is what is the relative value of each GT at the period when it will be "used and useful".

Therefore, if there is a significant decrease in useful power, and hence a similar decrease in value, then we turn to the consideration of what is the additional TIC value proposition for those plants so equipped. In the following table we see the relative net improvement in power output at the alternative rating point of 95°F. The before case has no TIC, and the after case has TIC with chilling down to 50°F (10C). The auxiliary load required to operate the chiller plant has been netted out of the after value.

GT OEM	Model	Version		Output at 95F, net	Chilled Output, net	Power Increase, net
				kW	kW	%
Alstom	**GT11**	N2		98,400	111,000	12.8%
Alstom	**GT11**	NM		74,570	85,700	14.9%
Alstom	**GT13**	E2		146,000	166,000	13.7%
GE	**PG5371**	PA		21,610	25,420	17.6%
GE	**PG6581**			36,130	41,180	14.0%
GE	**PG7241FA**	SC		146,500	169,250	15.5%
GE	**PG7241FA**	CC		442,700	499,300	12.8%
GE	**LM2500**	PE		19,370	21,800	12.5%
GE	**LM6000**	Sprint, DLN		37,800	45,560	20.5%
GE	**LM6000**	PC w/o IGV		29,000	43,240	49.1%
GE	**LM6000**	PD, DLN		30,390	41,700	37.2%
MHI	**MF111B**			12,260	14,120	15.2%
PWPS	**FT-8**	Twin		40,950	50,060	22.2%
PWPS	**FT-8+**	Twin		45,830	54,190	18.2%
RR	**Trent 50**			39,470	51,120	29.5%
Solar	**Titan 130**			11,410	13,620	19.4%
Solar	**Taurus 60**	T7800		4,522	5,225	15.5%
SWPC	**GT 10**	B		19,950	23,650	18.5%
SWPC	**GT 10**	C		23,591	27,920	18.4%
SWPC	**GT 35**			13,110	16,190	23.5%
SWPC	**GTX100**			36,090	41,520	15.0%
SWPC	**W251**	B11-12		40,840	47,560	16.5%

Table 4 Power increase due to TIC, at 95F Rating Point

There is little argument that TIC systems can significantly increase the amount of power from a GT at these high ambient conditions. The only area of misunderstanding for some engineers is in the area of value proposition. That is, is the unit cost of a chilled gas turbine less than the unit cost of an unchilled gas turbine? Because, after all, we know that there is not an unlimited budget to provide auxiliary equipment to our power projects. The following table shows that although the capital costs increase for a chilled plant, the incremental power increases faster. Therefore, the relative value of the plant improves, indicating a decrease in unit cost in many cases greater than 15%.

GT OEM	Model	Version	Installed Cost	Output at 95F, net	Net Unit Cost @ 95F		Installed Cost Chilled	Chilled Output, net	Unit Cost @ 95F, Installed	Unit Cost Change
			USD	kW	$ / kW		USD	kW	$ / kW	
Alstom	**GT11**	N2	$39,423,560	98,400	$401		$44,113,256	111,000	$397	-0.8%
Alstom	**GT11**	NM	$31,897,059	74,570	$428		$35,891,674	85,700	$419	-2.1%
Alstom	**GT13**	E2	$52,883,930	146,000	$362		$59,025,382	166,000	$356	-1.8%
GE	**PG5371**	PA	$16,429,308	21,610	$760		$18,256,644	25,420	$718	-5.5%
GE	**PG6581**		$22,007,985	36,130	$609		$24,154,674	41,180	$587	-3.7%
GE	**PG7241FA**	SC	$50,701,500	146,500	$346		$56,701,500	169,250	$335	-3.2%
GE	**PG7241FA**	CC	$212,400,000	442,700	$480		$224,400,000	499,300	$449	-6.3%
GE	**LM2500**	PE	$16,958,763	19,370	$876		$18,273,515	21,800	$838	-4.3%
GE	**LM6000**	Sprint, DLN	$24,032,157	37,800	$636		$26,055,401	45,560	$572	-10.0%
GE	**LM6000**	PC w/o IGV	$20,264,567	29,000	$699		$22,353,107	43,240	$517	-26.0%
GE	**LM6000**	PD, DLN	$20,951,135	30,390	$689		$23,011,843	41,700	$552	-20.0%
MHI	**MF111B**		$12,121,797	12,260	$989		$13,264,137	14,120	$939	-5.0%
PWPS	**FT-8**	Twin	$28,145,580	40,950	$687		$30,560,484	50,060	$610	-11.2%
PWPS	**FT-8+**	Twin	$30,250,300	45,830	$660		$32,711,367	54,190	$604	-8.5%
RR	**Trent 50**		$29,124,686	39,470	$738		$31,478,755	51,120	$616	-16.5%
Solar	**Titan 130**		$9,979,823	11,410	$875		$11,075,352	13,620	$813	-7.0%
Solar	**Taurus 60**	T7800	$4,935,830	4,522	$1,092		$5,538,968	5,225	$1,060	-2.9%
SWPC	**GT 10**	B	$15,365,096	19,950	$770		$16,802,378	23,650	$710	-7.8%
SWPC	**GT 10**	C	$16,404,096	23,591	$695		$18,605,143	27,920	$666	-4.2%
SWPC	**GT 35**		$12,132,993	13,110	$925		$13,756,030	16,190	$850	-8.2%
SWPC	**GTX100**		$22,574,088	36,090	$625		$24,499,581	41,520	$590	-5.7%
SWPC	**W251**	B11-12	$24,648,037	40,840	$604		$27,053,295	47,560	$569	-5.7%

Table 5 TIC's Economic Improvement to Unit Cost at 95F Rating Point

GT OEM	Model	Version	Installed Cost	Chilled Output, net	Installed Cost Chilled	net delta	TIC Cost	TIC unit cost
			USD	kW	USD			$ / kW
Alstom	**GT11**	N2	$39,423,560	111,000	$44,113,256	12,600	$4,689,696	$372
Alstom	**GT11**	NM	$31,897,059	85,700	$35,891,674	11,130	$3,994,615	$359
Alstom	**GT13**	E2	$52,883,930	166,000	$59,025,382	20,000	$6,141,452	$307
GE	**PG5371**	PA	$16,429,308	25,420	$18,256,644	3,810	$1,827,336	$480
GE	**PG6581**		$22,007,985	41,180	$24,154,674	5,050	$2,146,689	$425
GE	**PG7241FA**	SC	$50,701,500	169,250	$56,701,500	22,750	$6,000,000	$264
GE	**PG7241FA**	CC	$212,400,000	499,300	$224,400,000	56,600	$12,000,000	$212
GE	**LM2500**	PE	$16,958,763	21,800	$18,273,515	2,430	$1,314,751	$541
GE	**LM6000**	Sprint, DLN	$24,032,157	45,560	$26,055,401	7,760	$2,023,244	$261
GE	**LM6000**	PC w/o vIGV	$20,264,567	43,240	$22,353,107	14,240	$2,088,541	$147
GE	**LM6000**	PD, DLN	$20,951,135	41,700	$23,011,843	11,310	$2,060,708	$182
MHI	**MF111B**		$12,121,797	14,120	$13,264,137	1,860	$1,142,340	$614
PWPS	**FT-8**	Twin	$28,145,580	50,060	$30,560,484	9,110	$2,414,904	$265
PWPS	**FT-8+**	Twin	$30,250,300	54,190	$32,711,367	8,360	$2,461,067	$294
RR	**Trent 50**		$29,124,686	51,120	$31,478,755	11,650	$2,354,069	$202
Solar	**Titan 130**		$9,979,823	13,620	$11,075,352	2,210	$1,095,529	$496
Solar	**Taurus 60**	T7800	$4,935,830	5,225	$5,538,968	703	$603,138	$858
SWPC	**GT 10**	B	$15,365,096	23,650	$16,802,378	3,700	$1,437,283	$388
SWPC	**GT 10**	C	$16,404,096	27,920	$18,605,143	4,329	$2,201,048	$508
SWPC	**GT 35**		$12,132,993	16,190	$13,756,030	3,080	$1,623,037	$527
SWPC	**GTX100**		$22,574,088	41,520	$24,499,581	5,430	$1,925,493	$355
SWPC	**W251**	B11-12	$24,648,037	47,560	$27,053,295	6,720	$2,405,258	$358

Table 6 Unit Cost of TIC Installation, at 95F Rating Point

Revisiting the "Performance Index" for Gas Turbines

Jerry Ebeling of Burns & MacDonnell was one of the early A/E pioneers in TIC. In an ASME paper delivered in 1995[7], Kitchen and Ebeling described a formula for the "effectiveness" or "performance index", measuring the impact of ambient temperature and inlet cooling on various gas turbines. The purpose of this work was to determine which GTs were the best *candidates* for inlet cooling. Each gas turbine design has a unique personality, based on specific airflow (pounds of air per kW-Hr), compression ratio, and firing temperature.

The *performance index* is updated in this paper in a different format by considering how much parasitic load is required for chiller operation, as compared to the gross power increase due to TIC. This new factor will look much like a chiller "Coefficient of Performance" (COP), but we will call the "Chiller Multiplier". The terms are gross additional power associated with chilling divided by the amount of power required to operate the chiller. Because both terms have "kW" as units, this is a dimensionless parameter. This parameter shows that the amount of power required to run a chiller plant is returned at least four-fold, and is some exceptional cases, as much as 10X.

GT OEM	Model	Version	Chilled Air Flow	tons	kW per ton	chiller kW	gross delta power	Chiller multiplier
			kpph	1.626				
Alstom	GT11	N2	3,110	5,057	0.75	3,793	16,393	4.32
Alstom	GT11	NM	2,504	4,071	0.75	3,053	14,183	4.65
Alstom	GT13	E2	4,191	6,815	0.75	5,111	25,111	4.91
GE	PG5371	PA	986	1,603	0.75	1,202	5,012	4.17
GE	PG6581		1,162	1,889	0.75	1,417	6,467	4.56
GE	PG7241FA	SC	3,580	5,821	0.75	4,200	26,950	6.42
GE	PG7241FA	CC	7,160	11,642	0.75	8,400	65,000	7.74
GE	LM2500	PE	542	881	0.75	661	3,091	4.68
GE	LM6000	Sprint, DLN	1,038	1,687	0.75	1,265	9,025	7.13
GE	LM6000	PC w/o IGV	1,017	1,653	0.75	1,240	15,480	12.49
GE	LM6000	PD, DLN	1,016	1,652	0.75	1,239	12,549	10.13
MHI	MF111B		443	720	0.75	540	2,400	4.44
PWPS	FT-8	Twin	1,343	2,183	0.75	1,637	10,747	6.56
PWPS	FT-8+	Twin	1,381	2,245	0.75	1,684	10,044	5.97
RR	Trent 50		1,231	2,002	0.75	1,501	13,151	8.76
Solar	Titan 130		388	631	0.75	473	2,683	5.67
Solar	Taurus 60	T7800	171	278	0.75	209	912	4.37
SWPC	GT 10	B	616	1,001	0.75	751	4,451	5.93
SWPC	GT 10	C	709	1,153	0.75	864	5,194	6.01
SWPC	GT 35		744	1,210	0.75	908	3,988	4.39
SWPC	GTX100		951	1,546	0.75	1,160	6,590	5.68
SWPC	W251	B11-12	1,373	2,232	0.75	1,674	8,394	5.01

Table 7 TIC Multiplication Effect @ T_1=95F (35C) and T_2=50F (10C)

[7] Kitchen and Ebeling, 1995. Qualifying combustion turbines for inlet air cooling capacity enhancement. Paper 95-GT-266, *Int'l Gas Turbine and aerospace Cong.*, ASME

Conclusion

Given the extremes that some project developers have gone to reduce the cost of equipment and installation, we believe that the value proposition of TIC has been completely missed. Many GTs in the past seven years did not benefit from TIC in the design of the plant. In their zeal to save capital cost, many decision-makers short-changed the operations of their unit in such a way that they have failed to optimize the operational economics of the plant.

Simply said – they failed to put their money into the part of the plant that would have made them the most profit.

If such developers were ever called in to regulatory hearings after a major summer blackout, they would certainly be questioned as to whether their capital-saving decisions were “prudent”. Unfortunately, “merchant” IPP peakers do not have the same obligation to serve that their regulated counterparts are required to meet. Nonetheless, this message needs to be understood by state regulators and regional ISO’s: plants that are said to be providing capacity to serve peak loads need to be “all there” when the call comes to deliver. The only way to reliably predict the capacity level of a GT at all ambient temperatures is to “flat-line” that GT’s performance with TIC.

How do we now put this lesson into practice for the present and the future?

- Rising natural gas prices may cause a further devaluation of gas turbine plants. If there is another round of bankruptcies or forced plant sales, then we recommend to prospective owners, and their bankers, to considered the useful output of the plant at this alternate rating point.

- Existing facilities without TIC may assess their profitability or break-even costs if they now added TIC as a retrofit, to capture the maximum number of MW-Hrs with the greatest spark spread.

- Future gas-fired simple cycle and combined cycle plants need to carefully asses their realistic capacity factors, and the most likely hours of operation. The engineers and financiers alike must optimize their plans for the most profitable peaking season. Inclusion of TIC will allow the plant to be optimized at a high ambient temperature.

- Future IGCC plants need to consider how to flat-line the output of their plants. The operation of the gasification system should not be driven by hourly changes in GT fuel demand. The inclusion of a TIC system will help to normalize operations during hot weather.